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Spiky Strings on NS5-branes

Sagar Biswas

Department of Phyisics and Meteorology,
Indian Institute of technology Kharagpur,
Kharagpur-721 302, INDIA
E-mail: biswas.sagar09iitkgp@gmail.com

Kamal L. Panigrahi

Department of Physics and Meteorology & Centre for Theoretical studies,
Indian Institute of Technology Kharagpur,
Kharagpur-721302, INDIA
E-mail: panigrahi@phy.iitkgp.ernet.in

Abstract: We study rigidly rotating strings in the near horizon geometry of a stack of Neveu-Schwarz (NS) 5-branes. We solve the Nambu-Goto action of the fundamental string in the presence of a NS-NS two form ($B_{\mu\nu}$) and find out limiting cases corresponding to magnon and spike like solutions.

Keywords: D-branes.

Contents

1. Introduction

The conjectured AdS/CFT duality [1] has passed through various nontrivial tests in the past by analyzing the spectrum of quantum string states on AdS background and the spectrum of the anomalous dimensions of the $N = 4$ gauge theory operators in *planar limit*. Especially it has been noticed that in the semiclassical approximation the theory becomes *integrable* on the both sides of the duality. Though finding out the full spectrum of string theory in AdS background is difficult, it has been observed that in certain limits, for example in large angular momentum sector, the theory [2] is more tractable. In this region, one can use the semiclassical approximations to find the string spectrum as well [3]. The semiclassical string states in the gravity side has been used to look for suitable gauge theory operators on the boundary, in establishing the duality. In this connection, Hofman and Maldacena (HM) [5] considered a special limit [1] where the problem of determining the spectrum of both sides becomes rather simple. The spectrum consists of an elementary excitation known as magnon which propagates with a conserved momentum p along the spin chain. Further, a general class of rotating string solution in AdS_5 is the spiky string which describes the higher twist operators from dual field theory view point. Giant magnons can be thought of as a special limit of such spiky strings with shorter wavelength. Recently there has been a lot of work devoted for the understanding of the giant magnon and spiky string solutions in various backgrounds, see for example in [6]- [22]. There has also been numerous papers devoted for understanding the finite size corrections on these solutions, see [23, 24] and references therein.

In the present paper we generalize the discussion of spiky string in the near horizon geometry of a stack of NS5-branes [25]. In string theory NS5-branes are interesting because in the near horizon limit the theory on the worldvolume correspond to a nonlocal field

[1] The Hofman-Maldacena limit: $J \to \infty, \lambda = \text{fixed}, p = \text{fixed}, E - J = \text{fixed}$

theory, namely the little string theory (LST) [2]. Though the LST has not been understood properly until now, it seems a good exercise to analyze the solution in various limits and find out some operators in dual field theory if possible. The near horizon NS5-brane world sheet theory is exactly solvable, so from the bulk theory view point the theory is integrable. A little is known about the boundary theory, hence from that prospective it is rather hard to make definite statements about the exact nature of the theory. However it is interesting to study semiclassical spiky like string solution in the linear dilaton background and look for suitable operators in the boundary theory. Indeed such an attempt was made in [25] and the giant magnon solution with one angular momentum was found out. However, in deriving the same one had to look for limits where the background three form flux that supports the NS5-brane background vanishes. We would like to generalize that to a non-vanishing three form flux in the present paper. In deriving so, we find out a general class of rotating string solutions. In different limit, we found out solutions corresponding to giant magnon and spiky like string. The dispersion relation obtained is slightly different from that of the usual relation among various charges typically known for the case of two and three-spheres. The difference comes about because the presence of the background three form flux in the supergravity background which couples to the Fundamental string. The results can be compared with that of the solutions in the presence of background $\mathrm{B}_{\mathrm{NS-NS}}$ fields.

Rest of the paper is organized as follows. In the section-2, we write down the Nambu-Goto action for the rigidly rotating string in the near horizon limit of the NS5-brane background. We find various conserved charges, namely the total energy E, momenta along two angular direction (ϕ_1, ϕ_2) of the 3- sphere in the transverse direction of NS 5-brane, momenta along the five longitudinal directions of NS5-branes, y^i, and another conserved charge D related to the radial motion of the string. In section-3, we analyze two different limits of the solution which correspond to magnon and single spike string. We adopt a particular regularization to find out the dispersion relation among various charges. Finally in section-4 we conclude with some discussions.

2. Rigidly rotating Strings in NS5-brane Background

In this section we study rigidly rotating string in the near horizon limit of a stack of NS5-branes[3]. The classical solution of N NS5-brane is given by the following form of metric, NS-NS two form ($B_{\mu\nu}$) field and the dilaton,

$$ds^2 = -d\tilde{t}^2 + d\tilde{y}_i^2 + H(r)\left(dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi_1^2 + \cos^2\theta d\phi_2^2)\right)$$

$$e^{2(\phi-\phi_0)} = H(r), \;\; B = 2N\sin^2\theta d\phi_1 \wedge d\phi_2, \;\; H(r) = 1 + \frac{N{l_s}^2}{r^2} \tag{2.1}$$

where y^i, $i = 5, 6, 7, 8, 9$ label the world-volume directions of NS5-brane, and $H(r)$ is the harmonic function in the transverse space of the NS5-branes, l_s is the string length. In

[2] For review, see [26, 27].

[3] some aspects of string dynamics in NS5-brane background is studied for example in [28]

the near horizon limit, $r \to 0$, one can ignore 1 in $H(r)$, and the solution would look like (defining $\tilde{t} = \sqrt{N} l_s t, \tilde{y_i} = \sqrt{N} l_s y_i$)

$$\begin{aligned} ds^2 &= N{l_s}^2 \left(-dt^2 + d\theta^2 + \sin^2\theta d\phi_1^2 + \cos^2\theta d\phi_2^2 + \frac{dr^2}{r^2} + dy_i^2 \right), \\ e^{2(\phi-\phi_0)} &= \frac{N{l_s}^2}{r^2}, \;\; B = 2N\sin^2\theta d\phi_1 \wedge d\phi_2, \end{aligned} \tag{2.2}$$

To proceed further it is convenient to introduce the variable ρ that is related to r as

$$\rho = \ln \left(\frac{r}{\sqrt{N{l_s}^2}} \right) \tag{2.3}$$

so that the metric becomes,

$$ds^2 = N{l_s}^2 \left(-dt^2 + d\theta^2 + \sin^2\theta d\phi_1^2 + \cos^2\theta d\phi_2^2 + d\rho^2 + dy_5^2 \right) \;, \tag{2.4}$$

with the two form $B_{\phi_1\phi_2}$ remaining the same. We wish to study rigidly rotating string in this background. The Nambu-Goto action of the string in the presence of a background B field is written as[4]

$$S = -\frac{\sqrt{\lambda}}{2\pi} \int d^2\sigma \left[\sqrt{\tilde{g}} + \epsilon^{\alpha\beta} B_{\mu\nu} \partial_\alpha X^\mu \partial_\beta X^\nu \right] \;, \tag{2.5}$$

where

$$\tilde{g}_{\alpha\beta} = G_{\mu\nu} \partial_\alpha X^\mu \partial_\beta X^\nu \tag{2.6}$$

is the induced metric on the string world sheet and the pre factor $\sqrt{\lambda} = N$ is the ‘t Hooft coupling constant. The Lagrangian is given by

$$\begin{aligned} \mathcal{L} = &- \Big(\Big[(-\dot{t}t' + \dot{\theta}\theta' + \sin^2\theta \dot{\phi}_1 {\phi'}_1 + \cos^2\theta \dot{\phi}_2 {\phi'}_2 + \dot{\rho}\rho' + \dot{y}_i {y'}_i)^2 \\ &- (-\dot{t}^2 + \dot{\theta}^2 + \sin^2\theta \dot{\phi_1}^2 + \cos^2\theta \dot{\phi_2}^2 + \dot{\rho}^2 + \dot{y_i}^2)(-{t'}^2 + {\theta'}^2 + \sin^2\theta {\phi'}_1^2 + \cos^2\theta {\phi'}_2^2 + {\rho'}^2 + {y'}_i^2) \Big]^{1/2} \\ &+ 2\sin^2\theta \left(\dot{\phi_1}{\phi'}_2 - \dot{\phi_2}{\phi'}_1 \right) \Big) \end{aligned} \tag{2.7}$$

For further analysis we choose the following ansatz

$$t = \kappa\tau; \; \theta = \theta(\sigma); \; \phi_1 = \nu_1\tau + \sigma; \; \phi_2 = \nu_2\tau + \phi(\sigma); \; \rho = m\tau; \; y_i = v_i\tau \tag{2.8}$$

The Euler-Lagrangian equations derived from the above action are given by

$$\partial_\sigma \frac{\partial \mathcal{L}}{\partial t'} + \partial_\tau \frac{\partial \mathcal{L}}{\partial \dot{t}} = \frac{\partial \mathcal{L}}{\partial t} \tag{2.9}$$

$$\partial_\sigma \frac{\partial \mathcal{L}}{\partial \rho'} + \partial_\tau \frac{\partial \mathcal{L}}{\partial \dot{\rho}} = \frac{\partial \mathcal{L}}{\partial \rho} \tag{2.10}$$

[4]in the classical approximation (large ‘t Hooft coupling) we can ignore the dilaton coupling.

$$\partial_\sigma \frac{\partial \mathcal{L}}{\partial \phi_1'} + \partial_\tau \frac{\partial \mathcal{L}}{\partial \dot{\phi}_1} = \frac{\partial \mathcal{L}}{\partial \phi_1} \tag{2.11}$$

$$\partial_\sigma \frac{\partial \mathcal{L}}{\partial \phi_2'} + \partial_\tau \frac{\partial \mathcal{L}}{\partial \dot{\phi}_2} = \frac{\partial \mathcal{L}}{\partial \phi_2} \tag{2.12}$$

$$\partial_\sigma \frac{\partial \mathcal{L}}{\partial y_i'} + \partial_\tau \frac{\partial \mathcal{L}}{\partial \dot{y}_i} = \frac{\partial \mathcal{L}}{\partial y_i} \tag{2.13}$$

First solving (2.9) and (2.11) we get

$$\phi' = \frac{\sin^2\theta(\alpha^2 C_1 - \kappa\nu_1 C_2 - \nu_2^2 C_1 \cos^2\theta + 2\kappa\nu_1\nu_2\sin^2\theta)}{\nu_2\cos^2\theta(\kappa C_2 - C_1\nu_1\sin^2\theta - 2\kappa\nu_2\sin^2\theta)} \tag{2.14}$$

and for θ, we get

$$\theta'^2 = \frac{(\kappa^2 - C_1^2)(\nu_1\sin^2\theta + \phi'\nu_2\cos^2\theta)^2}{C_1^2(\alpha^2 - \nu_1^2\sin^2\theta - \nu_2^2\cos^2\theta)} - \sin^2\theta - \phi'^2\cos^2\theta \tag{2.15}$$

Note that writing the above two equations, we have made use of the solutions obtained from (2.9) and (2.11). Further, C_1 and C_2 are integration constants and $\alpha = \sqrt{\kappa^2 - m^2 - v_i v^i}$. Note also that by looking on the background, the Lagrangian is invariant under the following translation

$$\begin{aligned} t'(\tau,\sigma) &= t(\tau,\sigma) + \epsilon_t, \quad \phi_1'(\tau,\sigma) = \phi_1(\tau,\sigma) + \epsilon_{\phi_1}, \quad \phi_2'(\tau,\sigma) = \phi_2(\tau,\sigma) + \epsilon_{\phi_2}, \\ \rho'(\tau,\sigma) &= \rho(\tau,\sigma) + \epsilon_\rho, \quad y_i'(\tau,\sigma) = y_i(\tau,\sigma) + \epsilon_{y_i} \ , \end{aligned} \tag{2.16}$$

where $\epsilon_t, \epsilon_{\phi_1}, \epsilon_{\phi_2}, \epsilon_\rho, \epsilon_{y_i}$ are constants. Hence the rigidly rotating string has a number of conserved charges, namely the total energy (E), angular momenta J_1, and J_2, and D, which comes from the translation of ρ, and five conserved charges, P_{y_i} coming from the translational invariance of the metric along y^i-directions. We will compute them and find out relation between them for different limits where one can compute them easily.

3. Limiting Cases

In this section, we will analyze two limiting cases corresponding to the usual single spike and giant magnon like solutions respectively. First we will look for the spike solution.

3.1 single spike

We choose the constants of motion appropriately, such that $\theta' \to 0$ as $\theta \to \frac{\pi}{2}$, the values of constants we get are

$$C_2 = \alpha + 2\nu_2, \quad C_1\alpha = \kappa\nu_1 \tag{3.1}$$

With these constants, the differential equations for θ and ϕ now becomes

$$\phi' = -\frac{\nu_1(\nu_2 + 2\alpha)\sin^2\theta}{\alpha^2 + 2\nu_2\alpha\cos^2\theta - \nu_1^2\sin^2\theta} \tag{3.2}$$

and

$$\theta' = \frac{\alpha\sqrt{3(\nu_2^2-\nu_1^2)}\sin\theta\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}}{\alpha^2+2\nu_2\alpha\cos^2\theta-\nu_1^2\sin^2\theta} \tag{3.3}$$

where

$$\sin\theta_0 = \frac{\alpha+2\nu_2}{\sqrt{3(\nu_2^2-\nu_1^2)}} \tag{3.4}$$

Now we compute the conserved quantities by the following relations. The energy is (define $T=\frac{\sqrt{\lambda}}{2\pi}$)

$$E = -2T\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'}\frac{\partial\mathcal{L}}{\partial\dot{t}} = \frac{2T\kappa(\alpha^2-\nu_1^2)}{\alpha^2\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}} \tag{3.5}$$

Angular momenta

$$J_1 = 2T\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'}\frac{\partial\mathcal{L}}{\partial\dot{\phi}_1} = -\frac{2T\nu_1}{\alpha\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\sin\theta[2(2\alpha+\nu_2)-3\alpha\cos^2\theta]d\theta}{\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}} \tag{3.6}$$

and

$$J_2 = 2T\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'}\frac{\partial\mathcal{L}}{\partial\dot{\phi}_2} = \frac{2T}{\alpha\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\sin\theta[2(\nu_1^2-\alpha^2)-3\alpha\nu_2\cos^2\theta]d\theta}{\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}} \tag{3.7}$$

Further we get more conserved quantities defined by

$$D = 2T\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'}\frac{\partial\mathcal{L}}{\partial\dot{\rho}} = \frac{2Tm(\alpha^2-\nu_1^2)}{\alpha^2\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}} \tag{3.8}$$

and

$$P_{y_i} = 2T\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'}\frac{\partial\mathcal{L}}{\partial\dot{y}_i} = \frac{2Tv(\alpha^2-\nu_1^2)}{\alpha^2\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta-\sin^2\theta_0}}\ . \tag{3.9}$$

Further, the difference in the angle between two end points of the string is

$$\Delta\phi = 2\int_{\theta_0}^{\theta_1}\frac{d\theta}{\theta'} = -\frac{2}{\alpha\sqrt{3(\nu_2^2-\nu_1^2)}}\int_{\theta_0}^{\frac{\pi}{2}}\frac{\nu_1^2\sin^2\theta-2\nu_2\alpha\cos^2\theta-\alpha^2}{\cos\theta\sin\theta\sqrt{\sin^2\theta-\sin^2\theta_0}} \tag{3.10}$$

Here we can see that all conserved quantities diverges, but the quantity

$$\left(T\Delta\phi-\sqrt{E^2-D^2-P_{y_i}^2}\right) = 2T\left(\frac{\pi}{2}-\theta_0\right) \tag{3.11}$$

is finite.

Further, one can regularize J_1 and J_2 by using the expression for E as follows

$$\tilde{J}_1 = J_1 - \frac{2\nu_1(\nu_2+2\alpha)}{\nu_1^2-\alpha^2}\sqrt{E^2-D^2-P_{y_i}^2} = \frac{6T\nu_1}{\sqrt{3(\nu_2^2-\nu_1^2)}}\cos\theta_0 \tag{3.12}$$

$$\tilde{J}_2 = J_2 + 2\sqrt{E^2-D^2-P_{y_i}^2} = -\frac{6T\nu_2}{\sqrt{3(\nu_2^2-\nu_1^2)}}\cos\theta_0 \tag{3.13}$$

and they hold the following dispersion relation

$$\tilde{J}_1 = \sqrt{\tilde{J}_2^2 - \frac{3\lambda}{\pi^2}\sin^2(\frac{\pi}{2} - \theta_0)}\ . \tag{3.14}$$

As pointed out earlier the above relation should be compared with the dispersion relation typically known for the case of S^3 with the presence of $B_{\mu\nu}$ field (b), [29] i.e.

$$\tilde{J}_1 = \sqrt{\tilde{J}_2^2 + \frac{\lambda}{\pi^2}(1 - b^2)\sin^2(\frac{\pi}{2} - \theta_0)} \tag{3.15}$$

3.2 Giant Magnon

Now we consider the opposite limit, where the constants are

$$\alpha = \nu_1, \quad \kappa C_2 = \nu_1 C_1 + 2\kappa\nu_2\ . \tag{3.16}$$

Substituting these we get the following differential equations for ϕ and θ,

$$\phi' = -\frac{\sin^2\theta(\nu_2 C_1 + 2\kappa\nu_1)}{\cos^2\theta(\nu_1 C_1 + 2\kappa\nu_2)} \tag{3.17}$$

and

$$\theta' = \frac{\sin\theta\sqrt{\sin^2\theta - \sin^2\theta_1}}{\cos\theta\sin\theta_1} \tag{3.18}$$

where

$$\sin\theta_1 = \frac{\nu_1 C_1 + 2\kappa\nu_2}{\kappa\sqrt{3(\nu_2^2 - \nu_1^2)}} \tag{3.19}$$

Now the conserved charges become, the energy (E) as

$$E = \frac{2T(\kappa^2 - C_1^2)}{\kappa\sqrt{3(\nu_2^2 - \nu_1^2)}}\int_{\theta_1}^{\frac{\pi}{2}} \frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta - \sin^2\theta_1}} \tag{3.20}$$

Angular momenta along ϕ_1 and ϕ_2, respectively, are

$$J_1 = -\frac{2T}{\kappa^2\sqrt{3(\nu_2^2 - \nu_1^2)}}\int_{\theta_1}^{\frac{\pi}{2}} \frac{\sin\theta[3\nu_1\kappa^2\cos^2\theta - (\nu_1 C_1^2 + 2\kappa\nu_2 C_1 + 3\nu_1\kappa^2)]d\theta}{\cos\theta\sqrt{\sin^2\theta - \sin^2\theta_1}} \tag{3.21}$$

and

$$J_2 = -\frac{6T\nu_2}{\sqrt{3(\nu_2^2 - \nu_1^2)}}\cos\theta_1 \tag{3.22}$$

Further conserved charges, derived from the translation along ρ and along y_i are

$$D = \frac{2Tm(\kappa^2 - C_1^2)}{\kappa^2\sqrt{3(\nu_2^2 - \nu_1^2)}}\int_{\theta_1}^{\frac{\pi}{2}} \frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta - \sin^2\theta_1}} \tag{3.23}$$

and

$$P_{y_i} = \frac{2Tv(\kappa^2 - C_1^2)}{\kappa^2\sqrt{3(\nu_2^2 - \nu_1^2)}}\int_{\theta_1}^{\frac{\pi}{2}} \frac{\sin\theta d\theta}{\cos\theta\sqrt{\sin^2\theta - \sin^2\theta_1}} \tag{3.24}$$

also the difference in the angle between two ends of the string is

$$\Delta\phi = 2\int_{\theta_0}^{\theta_1} \frac{d\theta}{\theta'} = \pi - 2\theta_1 = p \tag{3.25}$$

Thus we see that here J_2 and $\Delta\phi$ are finite and rest of the quantities diverge. We can further rescale the expression for energy $\sqrt{E^2 - D^2 - P_{y_i}^2}$ as

$$\tilde{E} = \frac{\nu_1 C_1^2 + 2\kappa\nu_2 C_1 + 3\nu_1\kappa^2}{\alpha(\kappa^2 - c_1^2)}\sqrt{E^2 - D^2 - P_{y_i}^2} \tag{3.26}$$

and then obtain the following dispersion relation

$$\tilde{E} - J_1 = \sqrt{J_2^2 - \frac{3\lambda}{\pi^2}\sin^2\frac{p}{2}}\ . \tag{3.27}$$

Once again this dispersion relation among energy and angular momenta should be compared with the relation obtained in case of S^3 in the presence of a NS-NS B field[29]. Note that in the above relation, the presence of the charge D ($\tilde{E}$ contains D) does not imply any new physical interpretation of the dispersion relation. It simply reflects the fact that the motion of the string along the radial direction in the near horizon limit of NS5-brane background is free.

4. Conclusions

In this paper we have studied rigidly rotating strings in NS5-brane background. We have found out a general class of solutions and have studied some limiting cases, which correspond to spiky strings. In the process we have used a particular type of regularization to derive the relationship among various conserved charges. We have found out the dispersion relation that is different from the usual dispersion relation of the giant magnon and spiky strings on S^3 [16]. This stems from the fact that the F-string couples to the NS-NS B-field that appears in the supergravity background of a stack of NS5-branes. Hence the solutions of the equations of motion for the F-string knows about it. The present study can be extended in various directions. First, the finite size corrections can be studied easily by following [23]. Further it would be challenging to study the boundary theory operators of the solutions presented here.

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